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SPACE CHARGE LIMITED TRANSPORT AND BUNCHING OF NON K-V BEAMS.(U)

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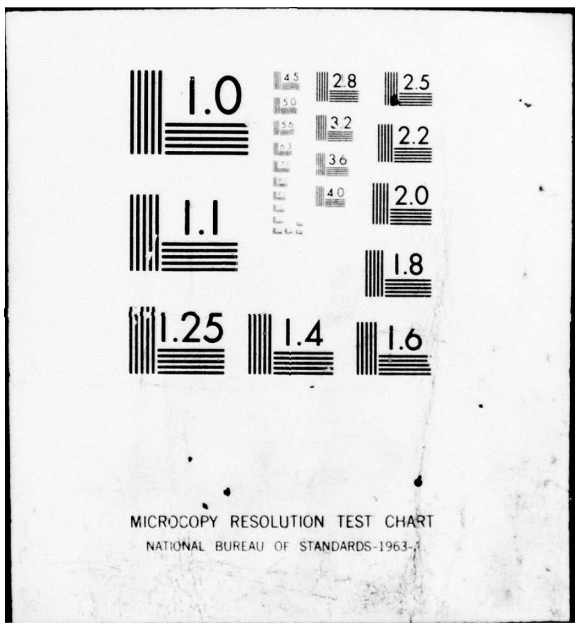
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NRL Memorandum Report 4050

Space Charge Limited Transport and Bunching of Non K-V Beams

I. Haber

Plasma Physics Division

July 25, 1979

NAVAL RESEARCH LABORATORY
Washington, D.C.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Particle simulations are used to examine the behavior of an intense beam propagating down an alternate gradient focusing channel. In order to examine the dependence of emittance growth on the particle distribution function, an initially low current, non K-V, matched distribution is established. The current is then slowly increased as the beam propagates down the channel. Differences are observed in both the current at which emittance growth begins, and the rate at which the emittance grows, when the form of the initial distribution is changed. But this emittance growth still limits the intensity of the beam being transported.		

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Space Charge Limited Transport and Bunching of Non K-V Beams*

INTRODUCTION

The possibility of using a beam of energetic heavy ions to ignite a thermonuclear pellet [1,2], has increased interest in the transport and focusing of high current low emittance beams. It has been established that a sufficiently intense particle beam is subject to transverse space charge driven instabilities[3-6] which can cause emittance growth, dilute the beam intensity, and interfere with both transport and focusing. The bulk of this work, however, has been done on beams having the theoretically tractable Kapchinskij-Vladimirskij [7] (K-V) distribution. A series of computer simulations has been performed to examine these space charge driven instabilities more generally by using a particle-in-cell model to follow the full non-linear behavior of non K-V systems. The behavior of the emittance growth during these simulations reinforces previous evidence that the current which can be stably transported is limited. But the rate at which the beam relaxes to this limit depends on the detailed form of the distribution function.

SUMMARY OF RESULTS

The numerical experiments described here employ a two-dimensional computer model[8] which follows the orbits of several thousand simulation particles in their self-consistent fields. The simulation is performed in a plane transverse to the direction of beam propagation in a reference frame moving with the beam. Any variation along the beam is assumed negligible in this frame. All simulations reported here have been performed assuming a thin lens alternate gradient transport system with a 90 degree phase advance per cell. Numerical tests[9,10] of the

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accuracy of this model have shown that the results are essentially independent of variations in numerical parameters such as time step, system resolution, and the number of particles when they are varied factors of two from the conditions used. In addition, excellent agreement with theoretical predictions has been obtained[3] during the early stages of the instability by comparing the growth rates and eigenfunction characteristics to theory in a case where only one mode is unstable.

It has previously been reported [11,12], that a K-V distribution with enough current to depress the tune from 90 degrees to 30 degrees goes rapidly unstable. After suffering an emittance growth of about a factor of two, the system reaches a steady state. Simulations at increased currents, however, behave differently. At these higher currents the initial period of rapid growth is followed by a period of slower growth. This slower growth does not appear to saturate until the ratio of current to emittance is reduced to a value which is relatively independent of the starting value. This suggests that there is a limiting current above which beam transport will be unstable, and the beam will suffer emittance growth until the ratio of current to emittance has returned to approximately this limiting value.

These simulations were performed using an initial K-V distribution. Because the actual beams in a transport system will not be precisely K-V in form, questions are raised about the quantitative applicability of these results. A series of numerical simulations has therefore been performed to explore the sensitivity of results, particularly with reference to emittance growth, to the detailed form of the distribution function.

In the absence of an analytic method for constructing non K-V high current equilibria in an alternate gradient transport system, an initial matched equilibrium is established at low current. The current is then linearly increased as the beam is transported through 100 pairs of thin lens magnets. This behavior is similar to what would occur in the center of a long beam being slowly bunched. After 100 magnet pairs the current has reached a value which would have corresponded to a depressed tune of 30 degrees had the distribution been K-V in form, and the emittance not grown. The current is then held constant while it traverses an additional 50 magnet pairs, so that the system has time to approach steady state.

Figure 1 is a plot of the rms emittances in the x and y directions for such an numerical experiment with the initial distribution K-V in form. After 60 magnet pairs, when the current has reached 0.6 of its final value, the emittance has started to grow indicating that the system has gone unstable. By the end of the run the emittance has grown to a value approximately 2.7 times its initial value.

Several other initial matched distributions have been run under similar conditions. The initial matched equilibrium is established as the sum of a set of K-V distributions. The radial profile is therefore the same for each of the various projections of the four dimensional X-Px-Y-Py phase space. The same initial rms emittance was used in each case. When this was done, distributions with a linear and quadratic fall off in radial profile showed emittance growths of only 1.7 and 2.0 respectively. The evolution of these rms emittances is shown in figures 2 and 3.

The least emittance growth, a factor of 1.5, was observed for a beam whose distribution is constructed of two populations. The first, containing three fourths of the particles, is a sum of K-V distributions with radial density falling quadratically to zero from the center. The second, containing the remaining quarter, has a linear falloff in density but goes to zero twice as far out as the first. The effect of this superposition is to give a distribution which falls off quadratically, except for a small linearly decreasing tail. Figure 4 is a plot showing the shape of this profile at the beginning of the simulation. Figure 5 is a plot of the evolution of a beam with this initial distribution. The evolution of this emittance is somewhat different from the one in which an initial K-V distribution was used. The growth begins earlier and is more gradual. It should be noted that this shape for the distribution was chosen because it closely resembled the profile actually obtained in previous simulation after the instability had saturated.

Table I lists some of the parameters associated with each of the distributions. The first two columns are the position and velocity of the particle with the maximum x and Px respectively (the edge of the distribution) normalized to the K-V distribution. The remaining columns show the final values (at $t=150$) of the maximum x velocity and position, and the rms valus of x, Px and the emittance. These are all normalized to the initial K-V values. For the K-V distribution the unstable fields scattered a small number of particles out of the numerical system so that the maximum position could not be measured. Note also that the final rms emittances are averaged between the x and y directions and so may be slightly different from the product of x and Px.

From these simulations it seems that it is possible to avoid the violently unstable behavior of a K-V distribution and also reduce the emittance growth by appropriately tailoring the initial distribution. This raises the question as to whether much higher beam intensities can be achieved by continuing this process and increasing the current further. From the evidence thus far obtained the answer appears to be negative. As the beam current is increased further, the resulting space charge forces have their maximum effect towards the center of the beam and less of an effect at the outermost tail particles. This results in a steepening of the beam distribution until the system looks closer to a K-V distribution and again becomes unstable.

Figure 6 shows the emittance growth that results when the distribution used in the simulation shown in figure 5 is bunched to a higher current. The current is increased in the same manner as the previous experiment but instead of being held constant after 100 magnets, the linear increase in current is maintained for another hundred magnets and then held constant for 50 more. This means that the final current is double that in the previous case.

In this case the total growth in emittance is approximately a factor of 2.8. The ratio of current to emittance, and therefore the beam intensity, has grown by only 7% despite a current growth by a factor of 2. Furthermore, the emittance is still increasing.

CONCLUSIONS

From the simulations run thus far it can be concluded that the growth rates for instabilities which are predicted on the basis of a K-V distribution may be higher than observed with a more realistic distribution. However, the conclusion reached previously that space charge instabilities limit the current intensities which can be stably transported appears to be reinforced. Furthermore, this limit appears to be close to what Maschke predicted [13] in 1976.

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Table I
Simulation Parameters

Distribution	Initial		Final				
	x_{max}	Px_{max}	x_{max}	Px_{max}	x_{rms}	Px_{rms}	ϵ_{rms}
K-V	1	1	—	10.2	2.0	1.4	2.7
Triangular	1.3	1.3	3.1	2.3	1.8	.9	1.7
Parabolic	1.2	1.2	3.0	2.4	1.8	1.0	2.0
Composite	1.8	1.8	2.9	2.1	1.7	.9	1.5

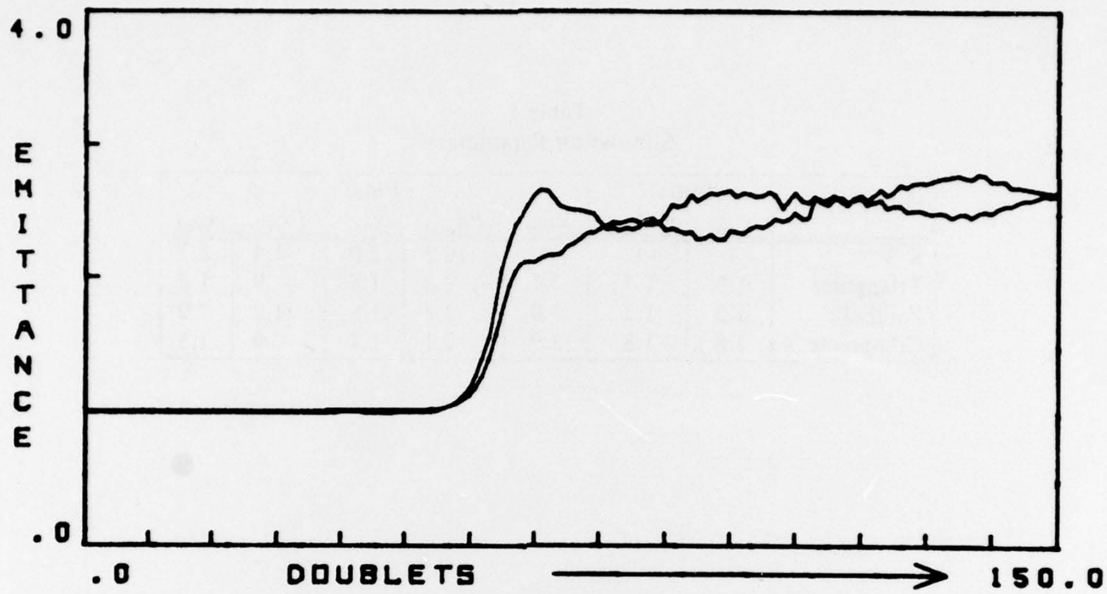

Figure 1. Evolution of *x* and *y* rms emittances for a K-V beam as the current is linearly increased for 100 magnet pairs and then held constant for another 50.

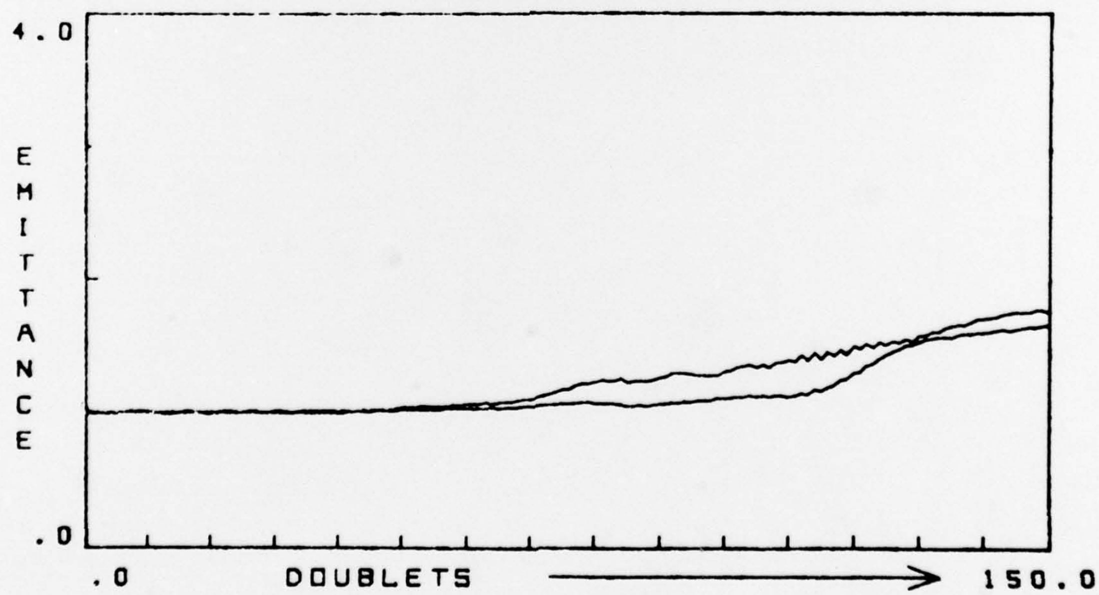

Figure 2. Evolution of rms emittances with increasing current. The initial distribution has a triangularly shaped radial profile.

Figure 3. Evolution of rms emittances with increasing current. The initial distribu'ion has a parabolically shaped radial profile.

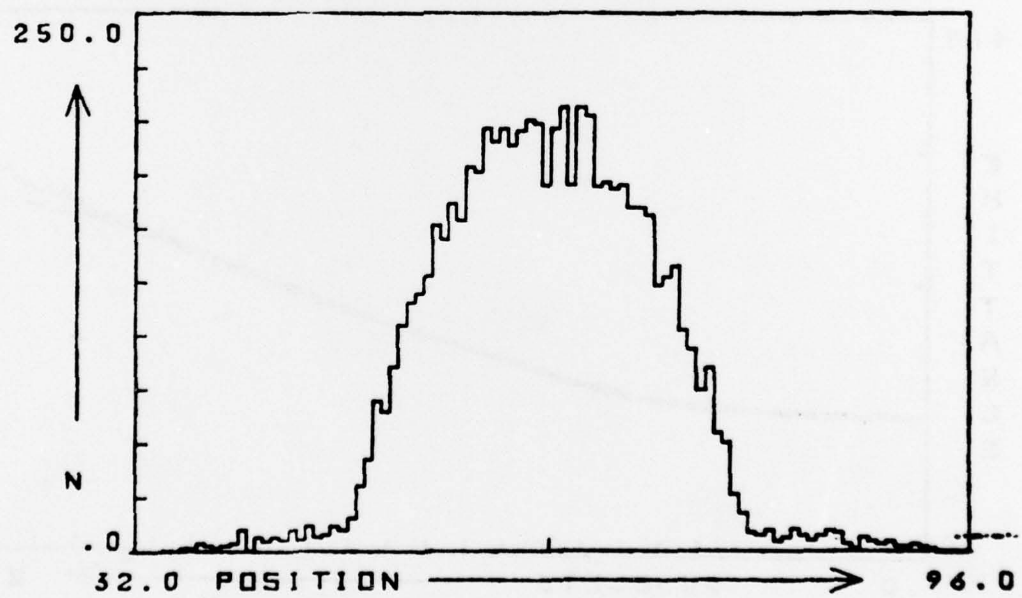

Figure 4. Measured cross section of the initial distribution with a radial profile decreasing quadratically with a small linearly decreasing tail.

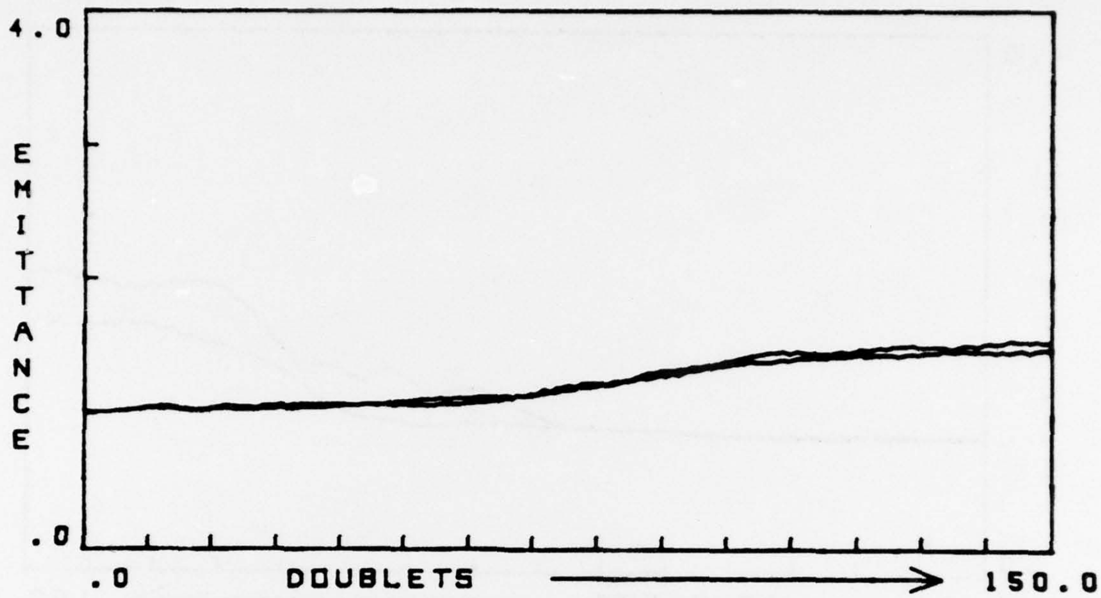

Figure 5. Evolution of rms emittance with increasing current. The initial distribution has a radial profile decreasing quadratically with a small linearly decreasing tail as shown in Fig. 4.

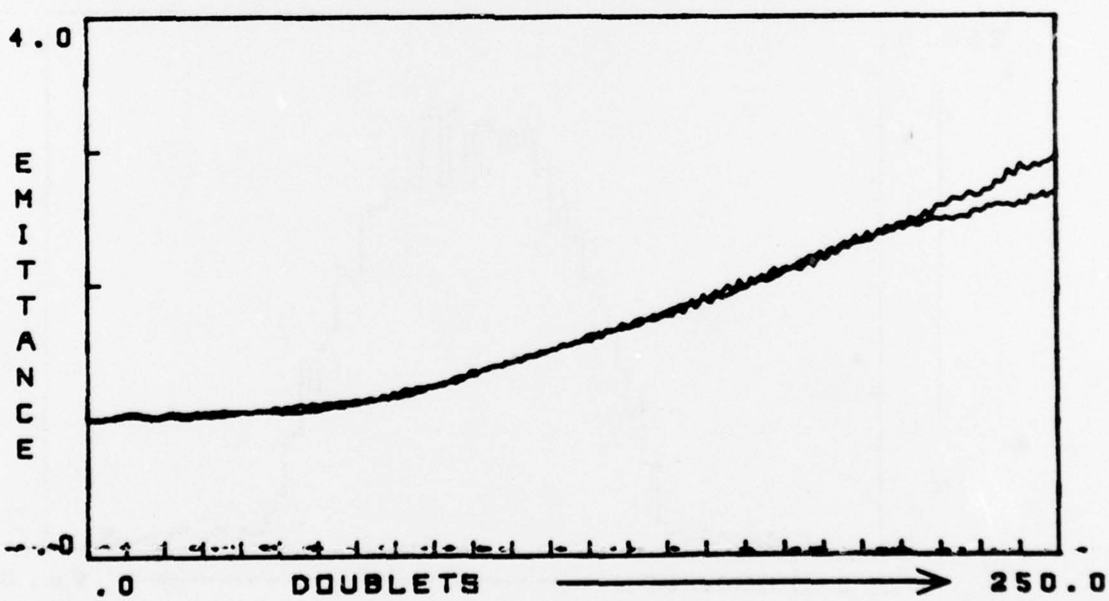

Figure 6. Evolution of the rms emittances as the linear current increases is maintained until the end current has doubled from the final value of Fig. 5. The emittance increase in this case has also nearly doubled.